Calculating the Energy Cost of CO_2 Removal in a Coal Based Gas Turbine Fuel Cell Hybrid Power Generation System with an Isolated Anode Stream.

Coal Based Fuel Cell Technology: Status, Needs and Future Applications, West Virginia University, Morgantown, WV, October 11-12, 2007

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Abstract:

In recent years there has been significant interest in identifying carbon capturing technologies that can be applied to fossil fuel power generation plants.CO_2 capture technologies seek to reduce the amount of CO_2 that would normally be emitted into the atmosphere from the daily operation of these plants. In terms of system efficiency and operating costs, this carbon capture is expensive. Further, the additional equipment that would be used to capture CO_2 emissions greatly adds to the complexity of the system.

There has also been significant interest in coal based gas turbine fuel cell hybrid power plants. A hybrid power plant can have much greater system efficiency than a normal gas turbine power plant because the heat that is normally unused in a standalone solid oxide fuel cell (SOFC) is recovered and used to drive a power producing turbine. It is thought that the increased system efficiency of the hybrid system might compensate for the increased expense of performing carbon capture.

In order to provide some analytical insight on this tradeoff we present a 100 MW class coal fired gas turbine SOFC hybrid power generation system. The hybrid system operates at a pressure ratio of 6, and uses heat recuperation and cathode air recirculation to control the SOFC inlet temperature and the temperature change across the SOFC. A carbon capture scheme is added to this system in order to calculate the relative energy cost in terms of system efficiency due to CO_2 compression. The carbon capture is performed by burning the unused fuel from the SOFC in an isolated anode stream using pure O_2 injection. The resulting heat that is generated from this process is then used to drive a secondary turbine that is placed in the anode exhaust stream where more work is extracted. With an isolated anode stream, the products of combustion from this secondary combustion process are mostly water and carbon dioxide. The water by-product is then condensed out of the stream leaving a relatively high concentration of CO_2. This is then compressed, and removed from the system. In this study we present power plant efficiency calculations for the performance of the hybrid system with the carbon capturing loop. Our results show the effects on system performance that result from a changing fuel utilization factor.

Hybrid System:

The hybrid system is powered by a coal derived syngas having the composition shown on Table 1. The lower concentration of methane allows us to do the calculations without a separate reforming reaction (internal or external to the fuel cell stack).

Species	Mole Fraction
CO	0.291
H_2	0.285
CO_2	0.118
H_2O	0.276
N_2	0.02991
CH_4	0.00009

Table 1. Composition of Syngas.

For these studies, the mass flow rate of the syngas is fixed at 14 kg/sec. The overall heating value for this fuel is calculated by Stultz, et al., to be 278 Btu/dscf[1]. The heating value is then converted to accommodate for the presence of water in the syngas, and a gasifier conversion efficiency of 80% is assumed. This conversion efficiency includes the energy cost of an air separation unit (ASU) which is needed to produce a source of pure oxygen from the gasification process. Together these effects reduce the overall fuel heating value to 201.3 Btu/scf which is the value that is used in the system efficiency calculations presented here. The syngas input stream thus delivers a power of approximately 150 MW that our hybrid system must convert to useful power.

The gas turbine fuel cell hybrid system with carbon capture loop is shown in Fig. 1. The hybrid system itself without the carbon capture loop follows the low pressure recuperated system presented by VanOsdol[2,3,4]. In the upper left hand corner a single shaft compressor-turbine pair is shown. The turbine in this pair, shown as TRB-CTH, is called the cathode turbine because it is solely driven by heat that is generated by the SOFC and picked up in the cathode air stream. In this arrangement the cathode turbine is a low temperature turbine operating with an inlet temperature of 1123 K which is equal to the SOFC outlet temperature. It therefore requires no cooling air.

There is also a heat recuperator for this system. The heat recuperator serves two purposes. It preheats the SOFC inlet air, and also increases the thermal efficiency of the gas turbine part of the cycle. As the pressure ratio drops the thermal efficiency of a recuperated gas turbine cycle increases, but the recuperator size increases. The system operating pressure is set by the compressor block that is upstream of the heat recuperator. For the present studies, the pressure ratio is fixed at 6.

The SOFC shown in the lower left hand corner of the figure is comprised of three Aspen flow blocks that operate in conjunction with a FORTRAN module. The mass flow rate of the fuel in this system is fixed at 14 kg/sec and enters the system model from the ANODEIN stream at the operating temperature of the SOFC. The fuel utilization factor is an input parameter which ranges from 0.8 to 0.9, which corresponds to a small range of SOFC power output.

The amount of heat that is recovered in the heat recuperator depends on the mass flow rates and temperatures of the fluid streams which enter and leave the device. This process is modeled using a heat exchanger effectiveness of 0.86. Because this is a passive process, it is a system parameter that is not directly controllable. So, in addition to the heat recuperation unit there must also be a cathode air recirculation path around the SOFC. This recirculation flow rate in this flow loop is driven by a high volume flow pressure recovery pump PRCVR-1. For a given fuel flow rate and system air flow rate the input power provided to this pump, and the output power demand on the SOFC can be used together to effectively control the SOFC inlet air temperature and temperature change across the SOFC. The SOFC output power is modeled using the fuel utilization factor. It is assumed that the SOFC power demand is commensurate with the fuel utilization factor input parameter.

Carbon capture is performed by taking the un-reacted fuel from the SOFC anode outlet stream shown in Fig. 1 as ANODEOUT and burning it in a separate combustion chamber BURN-H2 which is fed with a pure oxygen source stream. The source for this O_2 stream is the ASU which would be an integral part of the gasification process upstream of the syngas inlet stream. The amount of oxygen is regulated so that 99% of the unused hydrogen is oxidized. This leaves a post combustion mixture consisting mostly of high temperature carbon dioxide and water. This high temperature gas is then expanded in the anode turbine TRB-ANN to near atmospheric pressure extracting work. The stream leaving the anode turbine is still in a gaseous state with a temperature of 1079 K, so a condenser is added which removes the water and liberates heat. This high quality heat is then used to drive a steam bottoming cycle with an assumed overall conversion efficiency of 30%.

There is another recirculation loop around the anode turbine. This flow is driven by the recirculation compressor PRCVR-2 and is included in order to maintain the inlet temperature for the anode turbine at 1400 K. The final step in the carbon capture scheme is to compress the CO_2 outlet stream which consists mainly of low pressure CO_2 to 2000 psi where it may be disposed. One-stage compression without intercooling is used as a worst case scenario (other studies have considered multi-stage compression with intercooling for improved efficiency).

The hybrid system was modeled using the Aspen system simulation software. This software allows a user to set particular system parameters to a design specification while other selected system parameters continually change within convergence loops until they satisfy the design specifications that were set. For each run the mass flow rate of the syngas, system pressure ratio and the SOFC fuel utilization factor (FU) was held constant. The various pressure drops throughout the system are calculated according to the losses shown on Table. 2.

Aspen does not have a “Fuel Cell Block” that can directly calculate the performance of a fuel cell. However, from an assembly of flow separators/mixers and heat exchangers, and a FORTRAN block that calculates the reaction losses within a fuel cell, the performance of a fuel cell can be predicted. For example, by assuming that the mass flow rate of the fuel is known, and the fuel utilization factor for the SOFC is given, the amount of O_2 passing out of the cathode inlet air stream into the fuel cell is directly calculated. This O_2 then reacts with the H_2 and CO from the syngas inlet stream in the anode reaction block to produce heat. The initial temperature for this reaction is assigned an arbitrary value which determines the extent of the reaction. The total heat generated by the reaction is passed into the cathode heater block where it heats the oxygen depleted cathode air stream to the assigned temperature. The reaction temperature is then varied in a convergence loop until the residual heat from the cathode heater block and the electrical power equals the total change in the fuel's chemical potential. Additional convergence loops must be added to control the SOFC inlet temperature and the temperature change across the SOFC. This is done by changing the inlet compressor air flow and cathode air recirculation rate until the SOFC inlet temperature is 973 K and the temperature change across the SOFC is 150 K.

System Element	**Pressure Drop (% inlet pressure)**
Recuperator (cold side)	0.5
Recuperator (hot side)	0.5
SOFC	3.5
Combustion Loss	6.0
Bottom Loss	5.0

Table 2. Pressure losses for hybrid system.

Calculation results:

Calculations showing the effect of the fuel utilization factor on other system parameters are shown in Figs. 2-5. The system inlet flow rates and recirculation rates are shown in Figs. 2 and 3. For each case the syngas inlet flow rate is fixed. As the fuel utilization factor increases from 0.8 to 0.9 there is more heat generated by the SOFC. This heat affects both the SOFC inlet temperature and temperature change. The SOFC inlet temperature and temperature change are thus maintained at 973 K and 150 K in the system model by changing both the magnitude of system inlet air, and the cathode air recirculation flow. The cathode air recirculation rate is determined by the split ratio of Block B1 in Fig. 1. Because the overall system air flow increases with fuel utilization more than the cathode air recirculation flow, the cathode air recirculation rate as shown by the split ratio of block B1 in Fig. 1 shows little change.

The oxygen flow rate to the post combustion chamber shown in Fig. 2 naturally decreases with increasing fuel utilization. This is because there is less hydrogen that must be burned in the anode stream post combustion chamber. Figure 3 shows a corresponding decrease in the split ratio for block B3. This split ratio indicates the amount of flow recirculation around the anode turbine that is required to maintain the turbine inlet temperature at 1400 K As the heat that is generated in the post combustion chamber diminishes with increase fuel utilization, there is less recirculation required in order to keep the anode turbine inlet temperature at the desired 1400 K.

The power requirements for internal system compressors and the recirculation pumps are shown in Fig. 4. The principle energy cost in this system is the air compressor CMP-1 which is driven by the cathode turbine. This compressor pressurizes air and moves it through the system. This cost greatly increases with the fuel utilization as the amount of system air required to maintain SOFC temperatures also increases. The energy cost required to recirculate the cathode air flow also increases but is much less than the cost for the system air. The cost for anode gas recirculation naturally decreases with increased fuel utilization. The cost of compressing the CO_2 outlet stream remains relatively constant with changing fuel utilization. This cost is primarily a function of the carbon concentration in the syngas inlet stream. Wither the CO_2 is produced by combustion, or by the fuel cell, the amount that is produced remains relatively the same. It is the separation costs which are internal to the system that change with fuel utilization. This is the benefit of having an isolated anode stream.

The auxiliary power producers for this system are shown in Fig. 5. These are the powers produced by the anode turbine, the bottoming cycle which is not shown in system model, and the net power that is produced from the cathode turbine after the compressor power has been subtracted. There is available heat from the cooling of the anode expander outlet stream. It has been assumed that the sensible heat can be used in a steam cycle at an overall efficiency of 30%. It is interesting to note that there is more power produced by the anode turbine than by the cathode turbine net power. For low fuel utilization factor the anode turbine produces twice the power that the cathode turbine does. This ratio decreases with increasing fuel utilization until the point is reached where the ratio is closer to one. For higher fuel utilizations this ratio would be expected to be less than one.

The SOFC output power and the total system power are shown with their efficiency calculations in Fig. 6. The total system power is comprised of the SOFC output power and the three individual components that make up the auxiliary power producers that were shown in Fig. 5. It can be seen that the SOFC output power and efficiency both increase with increasing fuel utilization and that this increase is greater than the increase in the total system power and the total system efficiency. As the fuel utilization factor increases the SOFC output power and the net cathode turbine power increase, while the bottoming power and the anode turbine power both decrease. There is thus a shifting of power output from the less efficient power producers to a more efficient power producer. The overall system efficiency shown in Fig. 6 thus increases. But this increase is minor because of the decrease in anode auxiliary power and bottoming power. This cost offsets the efficiency gains from the SOFC.

The worst case energy cost of carbon capture can be calculated by taking the ratio of the power that is expended to compress the CO_2 outlet stream in one-stage divided by the total system output power. This ratio is calculated and shown in Fig. 7. The cost is approximately 11% of total system output. As fuel utilization increases this cost ratio is slightly reduced. At the higher fuel utilization the curve tend to flatten out. This shows that there may actually be optimum fuel utilization where there is no further benefit from making the SOFC any more efficient.

Summary:

The results show that by using a hybrid system with an isolated anode stream the cost of carbon capture would be dependent primarily on the amount of carbon in the syngas inlet stream. These results show that the gas turbine fuel cell hybrid system with heat recuperation, and with an isolated anode stream for performing carbon capture, may be a good candidate for power production in the future. This is because the overall system efficiency remains relatively high,,close to 50%, even with CO_2 compression costs as high as 11% of total system output power. These numbers are maintained even with deviations in the fuel utilization. Finally, we point out one benefit for this particular cycle design. Since this plant configuration shows relative insensitivity toward fuel utilization, the plant designer has freedom to consider a range of fuel utilizations with the objective of ensuring safe operation of the SOFC (and size of bottoming cycle as well) without significant impact to the plant efficiency.

Figures:

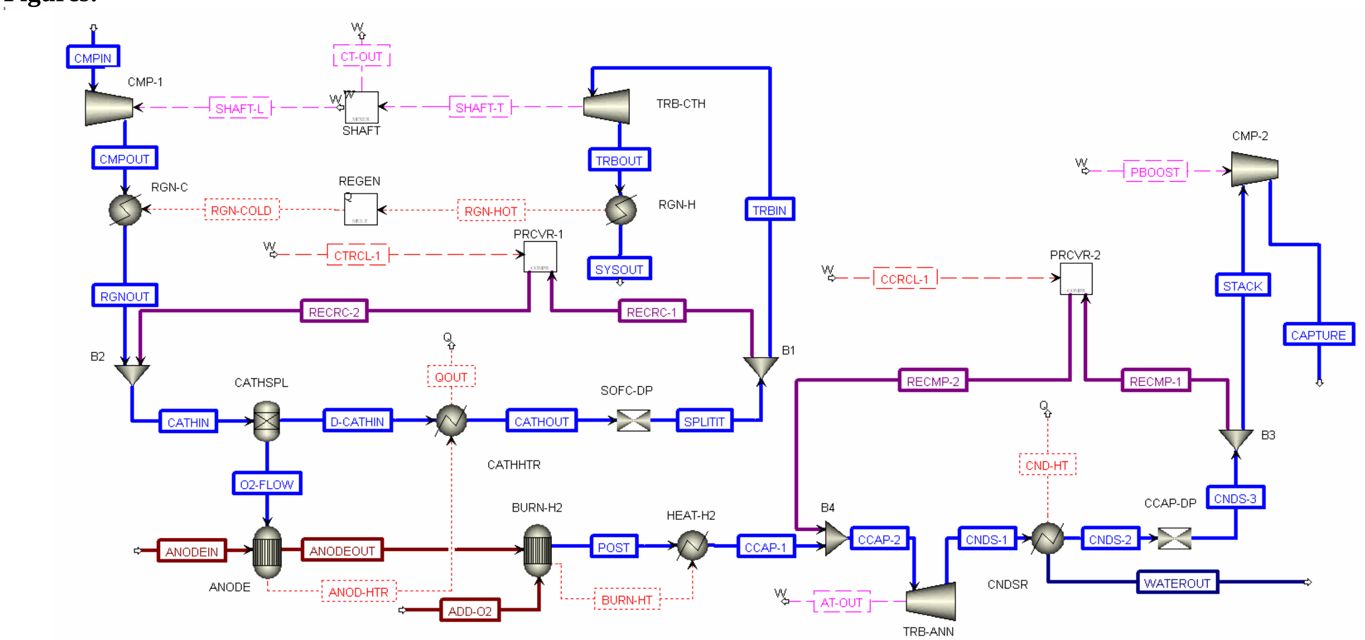

Figure 1. Gas turbine fuel cell hybrid system with carbon capture loop.

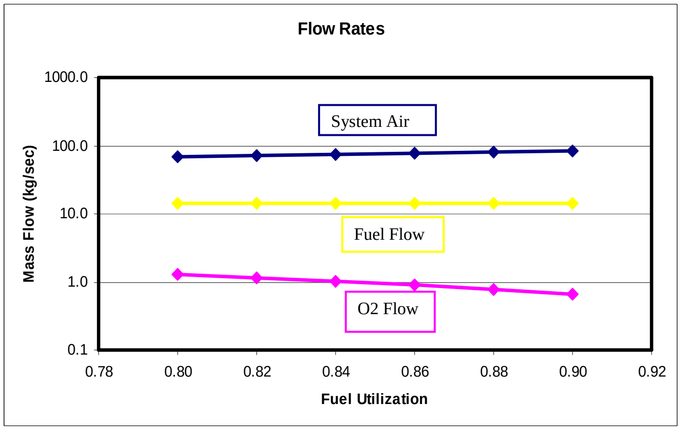

Figure 2. Inlet mass flow rates.

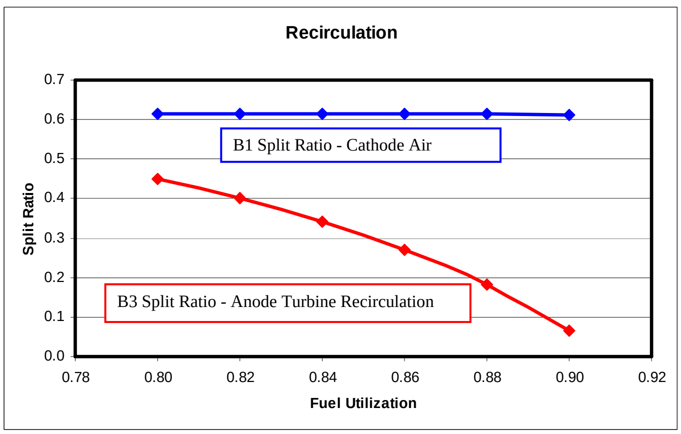

Figure 3. Recirculation rates.

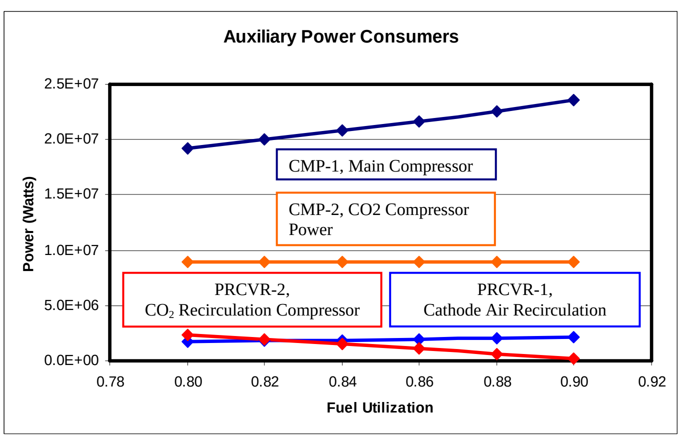

Figure 4. Power inputs.

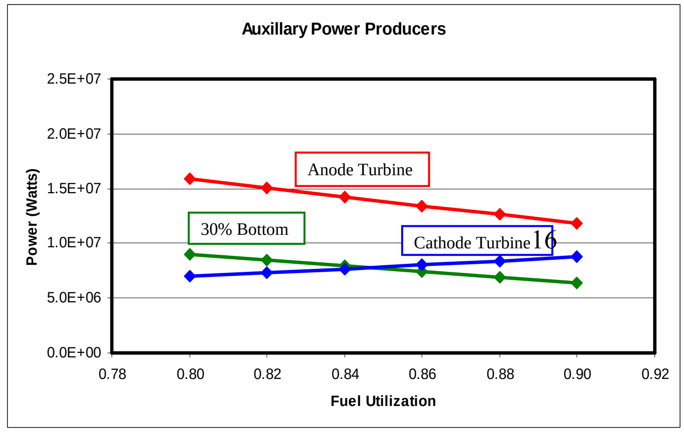

Figure 5. Power outputs.

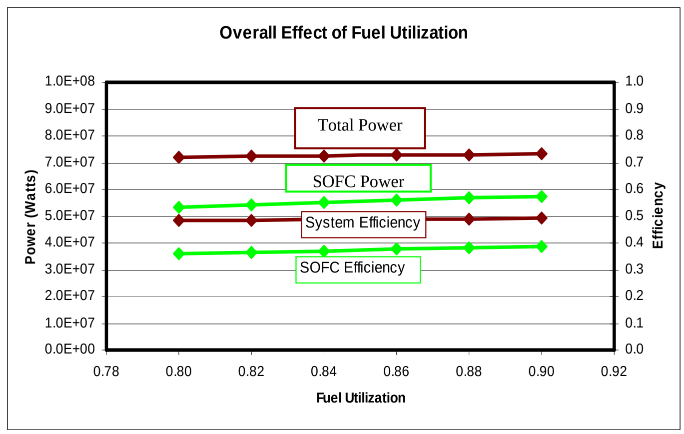

Figure 6. Total effect of fuel utilization.

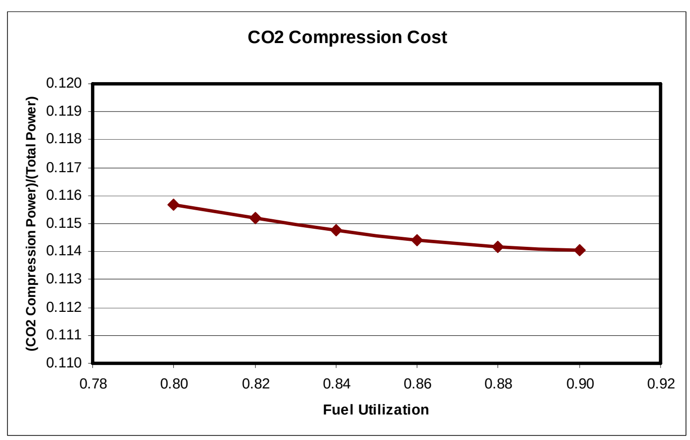

Figure 7. Energy Cost of CO2 Compression.

References:

1 S.C. Stultz, J.B. Kitto (eds.), Steam 40th ed., Babcock and Wilcox, 1992, pp. 17.1-17.17

2 D.Tucker, J.G.VanOsdol,.E.A.Liese, L.O.Lawson, S.E.Zitney, R.S. Gemmen, J.C.Ford, C. L.Haynes, "Thermal Management in a coal-Based SOFC Hybrid Through Numerical Simulation," 7th Annual SECA Workshop and Peer Review, Philadelphia, PA, September 12-14, 2006.

3. D.Tucker, J.G.VanOsdol,.E.A.Liese, L.O.Lawson, S.E.Zitney, R.S. Gemmen, J.C.Ford, C. L.Haynes, "Evaluation of Methods for Thermal Management in a Coal-Based SOFC Turbine Hybrid Through Numerical Simulation," International Colloquium on Environmentally Preferred Advanced Power Generation, Irvine, California, ICEPAG2006-24022, September, 2006.

4. John VanOsdol, Eric Liese, David Tucker, Randall Gemmen, Robert James, "Scaling a SOFC Gas Turbine Hybrid System to Meet a Range of Power Demand" 5th International Conference on Fuel Cell Science, Engineering and Technology, June 18th 2007, New York, USA